An Optimal Charging of Plug-In Electric Vehicles in Unbalanced Three-Phase Distribution Network

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Abstract—**Electric vehicles (EVs) are developing due to concerns over global warming and the major role of the transportation sector in emissions. EVs can also flatten the power curve and increase the reliability of power grids when renewable energy sources are used. Despite of these benefits, EVs impose new loads on distribution networks. Simultaneous charging of EVs, especially at high penetration levels, can create new load peaks in the power curves as well as overloading transformers, shortening their service life. In actual applications, most electric cars are single-phase loads that need to be charged from household or commercial outlets. In this paper, an optimization method is presented to coordinate the dynamic charge operation of single-phase EVs in an unbalanced three-phase distribution network. In the proposed method, the main goal of charging management is to minimize the total cost, which considers both network security constraints and electric vehicle constraints. The proposed method is tested on a sample distribution network and the numerical results prove the effectiveness of the method.**

Keywords—Charging strategy, Electric vehicle, Particle swarm optimization, Smart grids, Unbalanced distribution network.

I. INTRODUCTION

The number of electric vehicles (EVs) are growing, and their subsequent effects should be considered on the electric networks. It is important to adapt future development of the EVs charging with present network [1]. The development of EVs can address environmental issues like CO_2 emissions [2]. EVs have profound impact on the future of energy system.

The charging of EVs has effect on the electric network, which should be studied in different aspects. The method to simulate the charging of EVs is the key to analyze EVs' flexibility on the operation of distribution system [3]. Development of EVs without considering the suitable charging management leads to numerous diverse effects on electric network including increase in harmonics, voltage unbalance and so on.

In order to meet the problems related to large penetration of EVs in distribution networks, optimal charging strategies are addressed in previous studies. In [4], the EVs charging cost was minimized considering the day-ahead electricity price (DAEP) and battery degradation cost. In the study, different constraints including the EVs state of charge (SOC) restrictions, the EVs maximum power charger, full charging of the EVs' batteries at the end of the charging period and the distribution feeder power are considered.

Monte Carlo Simulations (MCS) have been applied to model the arrival and departure time distribution functions while the EV's initial SOC uncertainties are estimated based on their daily mileage. In [5], the EV's charging management was done in the discrete time approach. The objective function is minimizing the total cost related to buying electricity from external network, fossil fuel cost and the services provided for customers. The charging management is addressed by defining different objectives in previous studies.

In [6] was outlined a battery charging strategy to reduce charging losses in a lithium-ion battery for EVs. The proposed charging strategy utilizes an adaptive current profile based on variations in the battery internal resistance as a function of the state of charge and the charge rate. In [7], the EV's charging management is done in order to flatten the residential demand and minimize the charging cost.

In [8] was presented a charging management strategy of the Electric Vehicles to support the integration of renewable energy sources and distributed generation. In this study, the users' preferences (drivers) and the goal for realizing a scheduled aggregated power profile in order to minimize the effects of intermittency of the renewable energy sources have been studied.

The authors in [9] have proposed a real-time charging strategy for EVs in an unbalanced distribution network. However, the proposed method optimizes for single time steps. The effects of charging EVs in both balanced and unbalanced networks are studied in different references. In [10], the branch power flow equations of balanced and unbalanced distribution system were derived. The linearization methods for the nonlinear terms of the branch power flow equations were as well proposed. The charging strategy of EVs was addressed using a model predictive control method in order to minimize the total cost [11].

In [12], the application of battery energy storage systems (BESSs) was studied in order to face the increased load demand by the penetration of EVs in distribution networks considering photovoltaic units. A Particle Swarm Optimization (PSO) algorithm was developed in order to perform optimal charging schedule for the EVs under the aim of optimizing the distribution network voltage profile. In [13], the authors have divided the driving area into four zones according to the functional areas of distribution network, and a regional time-of-use (RTOU) electricity price model was proposed considering its spatial and temporal characteristics.

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The charging management problem of EVs including was modeled considering regional layer and node layer.

Many of the methods discussed above assume networks in balance position. However, a large number of EVs are charged in unbalanced distribution systems. It is important to study the problems related to unbalanced networks. Some of the discussed works have been optimized from the network operators' view, which can limit the incentive of EV owners to participate in the program.

In this work, an optimal charging method is presented in order to control charging rates of EVs in the unbalanced three-phase distribution networks. A PSO- based method is used in order to minimize the total charging cost of vehicles considering different application constraints. The studied constraints involve transformer and line limitations, phase unbalance and voltage limits. The proposed charging method decreases the overall energy costs while satisfying both the operational constraints and realistic model. The contribution of the study can be listed as follows:

- In this work the problems related to unbalanced networks are studied. an optimal charging method is presented in order to control charging rates of EVs in the unbalanced three-phase distribution networks;
- The proposed charging method decreases the overall energy costs while satisfying operational the constraints.

The rest of the manuscript is organized as follows: Section 2 provides the details of the proposed method. The proposed algorithm for charging management is presented in Section 3. Section 4 addresses the numerical and simulation results of the study considered. Finally, Section 5 provides the main findings of this work.

II. METHODOLOGY

This section provides the optimal charging of EVs in the unbalanced three-phase distribution networks with a comprehensive mathematical formulation.

A. *Assumptions*

The following assumptions are based on Australian Victoria EV trial as part of a pilot load control project [14]. It is assumed that EVs' charging rates are controlled centrally by the network operator through advanced metering infrastructure as a main part of smart grids technology.

In addition, certain knowledge of the network characteristics is necessary, i.e., network topology, line impedances/admittances, nominal voltages and loads.

B. *Objective Function*

The objective function of the proposed strategy is to minimize total charging cost of vehicles for following 24-hour horizon. The minimum charging cost can be considered as EV owners' main objective, which can be assumed as incentives for customers to permit network operator centrally controls their charging rates. The objective function is given as follows:

$$\begin{aligned} Total\ Cost = & \sum_{t\in ST}\sum_{i\in S_{ev}^{a}} P_{a,ch}(t,i)\Delta T^{t} P_r(t) \\ & + \sum_{t\in ST}\sum_{i\in S_{ev}^{b}} P_{b,ch}(t,i)\Delta T^{t} P_r(t) \\ & + \sum_{t\in ST}\sum_{i\in S_{ev}^{c}} P_{c,ch}(t,i)\Delta T^{t} P_r(t) \end{aligned} \tag{1}$$

where, $P_{a,ch}$, $P_{b,ch}$, and $P_{c,ch}$ are EVs' charging rate at phase a, b, and c of node ith during time step t, respectively. Cost of electricity at time step t is denoted by P_r.

C. *Constraints*

The objective function should be minimized subject to certain constraints. The following Equations guarantee that the voltage at phase a, b, and c of node ith during time step t are preserved within the rated voltage ranges indicated for the network:

$$V^{min} \le V_a(t,i) \le V^{max} \tag{2}$$

$$V^{min} \le V_b(t,i) \le V^{max} \tag{3}$$

$$V^{min} \le V_c(t,i) \le V^{max} \tag{4}$$

The maximum and minimum allowed network voltage levels are $V^{min}$and V^{max}, where assumed to be 0.9 pu and 1.1 pu, [15]. The large variations in charging rates are undesirable for battery technologies [16]. Therefore, the following equations are used to limit EVs' rate of changes:

$$P_{a,EV}(t-1,i) - \Delta \le P_{a,EV}(t,i) \le P_{a,EV}(t-1,i) + \Delta \tag{5}$$

$$P_{b,EV}(t-1,i) - \Delta \le P_{b,EV}(t,i) \le P_{b,EV}(t-1,i) + \Delta \tag{6}$$

$$P_{c,EV}(t-1,i) - \Delta \le P_{c,EV}(t,i) \le P_{c,EV}(t-1,i) + \Delta \tag{7}$$

where, $P_{a,EV}$, $P_{b,EV}$, and $P_{c,EV}$ are EVs' power demand at phase a, b, and c of node ith during time step t, respectively. Δ is a specified limit (kW) that denotes the allowable EVs' power demand change. EVs have the similar minimum and maximum possible power demand, i.e., $P_{EV,min}$ and $P_{EV,max}$, which is considered as follows:

$$P_{EV,min} \le P_{a,EV}(t,i) \le P_{EV,max} \tag{8}$$

$$P_{EV,min} \le P_{b,EV}(t,i) \le P_{EV,max} \tag{9}$$

$$P_{EV,min} \le P_{c,EV}(t,i) \le P_{EV,max} \tag{10}$$

The mathematical relations between charging rates and power demands of EVs are as follows:

$$P_{a,EV}(t,i) = \eta P_{a,ch}(t,i) \tag{11}$$

$$P_{b,EV}(t,i) = \eta P_{b,ch}(t,i) \tag{12}$$

$$P_{c,EV}(t,i) = \eta P_{b,ch}(t,i) \tag{13}$$

where, η is charging efficiency of batteries because of energy loss due to AC/DC conversion. Each EV has a target of reaching to a specified energy level which expressed as follows:

$$W_{a,EV}^{i} = \sum_{t=1}^{24} P_{a,EV}(t,i)\Delta T \tag{14}$$

$$W_{b,EV}^{i} = \sum_{t=1}^{24} P_{b,EV}(t,i)\Delta T \tag{15}$$

$$W_{c,EV}^{i} = \sum_{t=1}^{24} P_{c,EV}(t,i)\Delta T \tag{16}$$

where, $W_{a,EV}^{i}$, $W_{b,EV}^{i}$, and $W_{c,EV}^{i}$ are EVs' energy level at phase a, b, and c of node ith during time step t, respectively. The mathematical relation between energy level and state of charge of EVs are as follows:

$$SOC_{a}^{i} = SOC_{0,a}^{i} + \frac{W_{a,EV}^{i}}{C_{a}^{i}} \tag{17}$$

$$SOC_{b}^{i} = SOC_{0,b}^{i} + \frac{W_{b,EV}^{i}}{C_{b}^{i}} \tag{18}$$

$$SOC_{c}^{i} = SOC_{0,c}^{i} + \frac{W_{c,EV}^{i}}{C_{c}^{i}} \tag{19}$$

where, SOC_{a}^{i}, SOC_{b}^{i}, and SOC_{c}^{i} are batteries SOC at phase a, b, and c of node ith during time step t, respectively. C_{a}^{i}, C_{b}^{i}, and C_{c}^{i} determine batteries capacity. The thermal loading of transformer and line should be considered to protect this equipment as follows:

$$L_{TX} \leq L_{TX_{max}} \tag{20}$$

$$L_{MC} \leq L_{MC_{max}} \tag{21}$$

where, L_{TX} and L_{MC} are thermal loading, in kVA, for transformer and line, respectively. $L_{TX_{max}}$ and $L_{MC_{max}}$ determines the maximum loading for transformers and line, respectively.

III. PROPOSED ALGORITHM FOR OPTIMAL CHARGING

In this section the presented algorithm for optimal charging of EVs is discussed. The particle swarm optimization (PSO) technique is used in this manuscript to solve the optimization problem considering its constraints. An optimal result is attained through iterations of the evolution procedure from an initial value set. In this procedure, the particle's parameters are updated based on the former best results for that particle and for the swarm so far. More in details, the jth particle firstly begins from a random position $x_j^{(0)}$ with a velocity $v_j^{(0)}$. This position iteratively travels to another position $x_j^{(k)}$ at iteration k while continuously updating its velocity $v_j^{(k)}$ according to its own best experience $Pbest_j$, and the swarm's best knowledge $gbest_j$. This can be mathematically explained as follows:

$$\begin{aligned} v_j^{(k+1)} &= wv_j^{(k)} + c_1r_1\left(Pbest_j - x_j^{(k)}\right) \\ &\quad + c_2r_2\left(gbest_j - x_j^{(k)}\right) \end{aligned} \tag{22}$$

$$w = w_{max} - \frac{W_{max} - W_{min}}{k_{max}} \times k \tag{23}$$

$$x_j^{(k+1)} = x_j^{(k)} + v_j^{(k+1)} \qquad j = 1,2,\ldots\ldots,n \tag{24}$$

where, w, c_1, c_2, r_1, and r_2 are parameters of the PSO method. Using a trial and error approach the values of W_{max},W_{min},c_1 andc_2 are set to be 0.9, 0.4, 2 and 2. k increases from 1 to $k_{max} = 10$. r_1 and $r_2$are randomly selected between 0 and 1.

Figure 1 shows the PSO flowchart for the optimal charging strategy of EVs. The initial position of particles, i.e., EV's SOC, charging strategy, including charging rates and charging times, are randomly assigned.

Then, it should be verified that the EV's SOC and charging strategy are in contradiction with each other. If this condition is met, the charging strategies are modified considering EV's SOC. The charging strategies are imported to DIgSILENT software and load flow analysis results are exported to MATLAB software. If the load flow analysis is converged, the PSO objective function is evaluated. Otherwise, the PSO objective function is set to be infinite. If the PSO algorithm does not satisfy convergence criteria, the values of $x_j^{(k)}$, $v_j^{(k)}$, $Pbest_j$, and $gbest_j$ are updated for the next iteration.

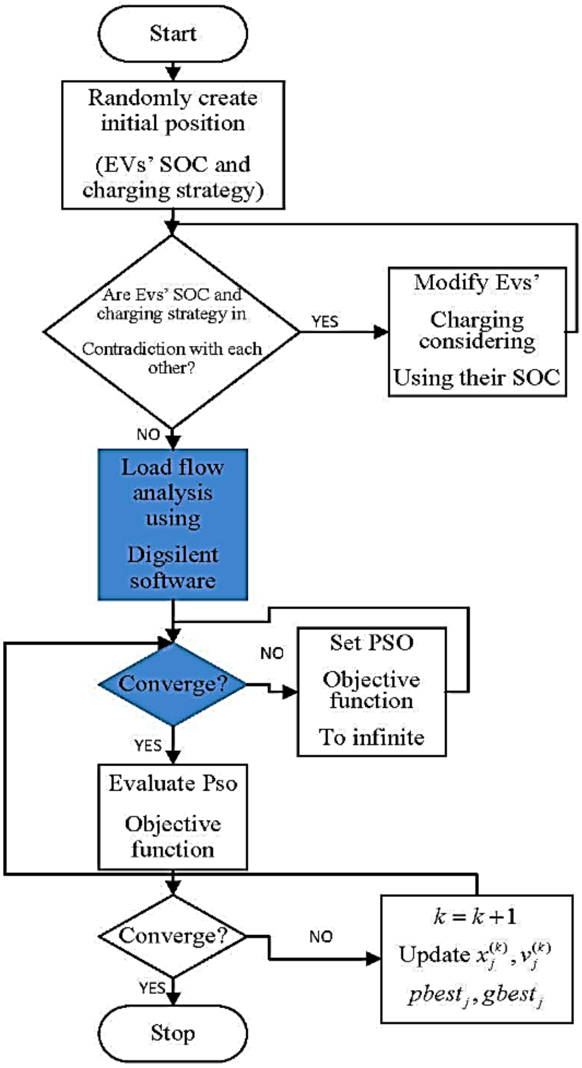

Figure 1.PSO flowchart for optimal charging strategy of EVs.

V. RESULTS AND DISCUSSION

Three-phase unbalanced power flow analysis is needed to determine network voltage and thermal loading levels. In this wok, DIgSILENT software is used to perform unbalanced power flow analysis which is the most powerful power system analysis package. To this end, firstly the EVs' charging is determined by solving the optimization problem by MATLAB software.

Then, these data, i.e., the EVs' charging data are imported to DIgSILENT software with DPL interface, and the load flow analysis is carried out. In this step, the output data of load flow are exported to MATLAB for more analysis. This exchange of data between MATLAB and DIgSILENT is continued until optimal results are obtained. The simulation data and results are explained as follows.

A. Data

The test network is based on the real distribution in the residential area of Dublin, Ireland. The single line diagram of this network and the technical data of the network and residential load demand are presented in [18]. Meanwhile, the capacity of main transformer is assumed to be 400 kVA while the maximum current of main lines is 424 A. Each EV is a single-phase load supplied by connected point of residential customers.

It is assumed that charging rates of EVs are same and 4 kW until 95% maximum capacity and 1.5 kW until full capacity. Moreover, the capacity of EV batteries is 20 kWh with 90% efficiency.

As shown in Figure 2, half of residential customers are randomly used an EV led to 67 EVs with maximum demand of 268 kW. The initial state-of-charge of EVs is randomly generated and shown in Figure 2. Moreover, the share of EVs between phases of network and their total energy demand are illustrated in Table I.

B. Simulations

The proposed strategy (Section III) is employed for a 24-hour time period. The convergence process of proposed algorithm is shown in Figure 3. It is shown that the optimal results are obtained in iteration 10 with less than 1 minute, decreasing the cost for about 0.9×10^4.

The charging strategies of EVs are illustrated in Figures 4 to 7. As can be seen, the EVs' charging time and rates are different between each other. Therefore, using optimal distribution of EVs' charging demand over 24-hour time period leads to smoother loads and reduction in EVs' charging cost.

The optimal number of EVs, versus charging start-time and number of EVs, versus charging durations are shown in Figures 8 and 9, respectively. As can be seen, start-time charging is mainly occurred in off-peak periods, so it helps to smooth load curve and decrease the expenditures.

Meanwhile, the charging durations is between 2 hour and 5 hours. It should be mentioned that average charging duration is about 5.34 hours. Moreover, network's constraints include transmission lines' and transformers' loadings and node voltage limits are met.

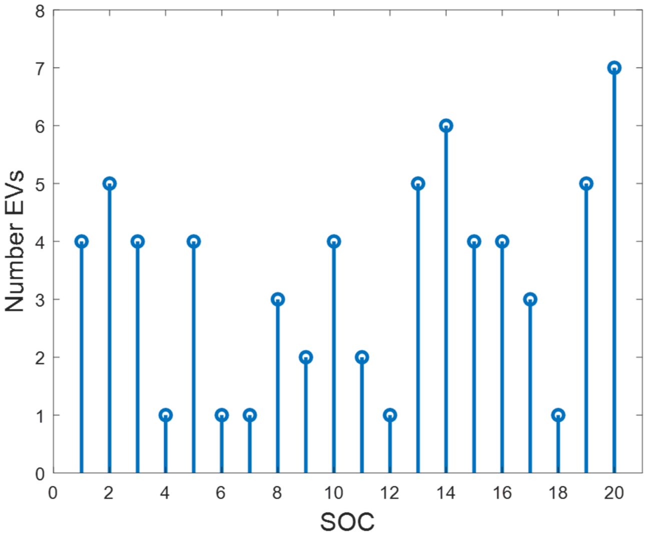

Figure 2. EVs' initial state-of-charge.

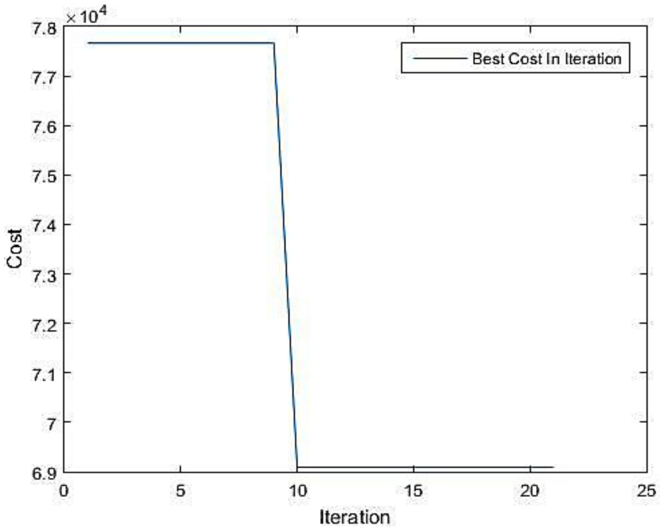

Figure 3. Convergence process of proposed algorithm.

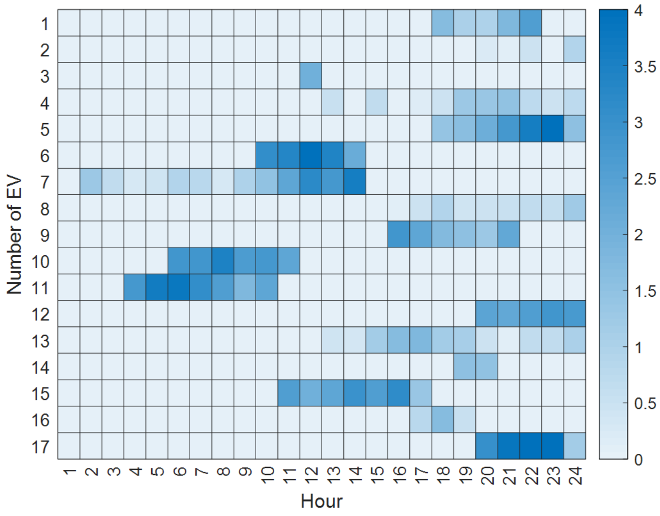

Figure 4. Optimal charging strategy of EV number 1 to 17.

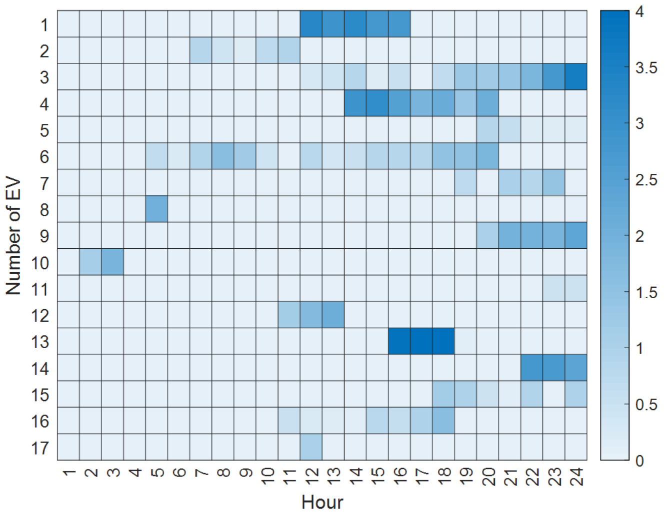

Figure 5. Optimal charging strategy of EV number 18 to 34.

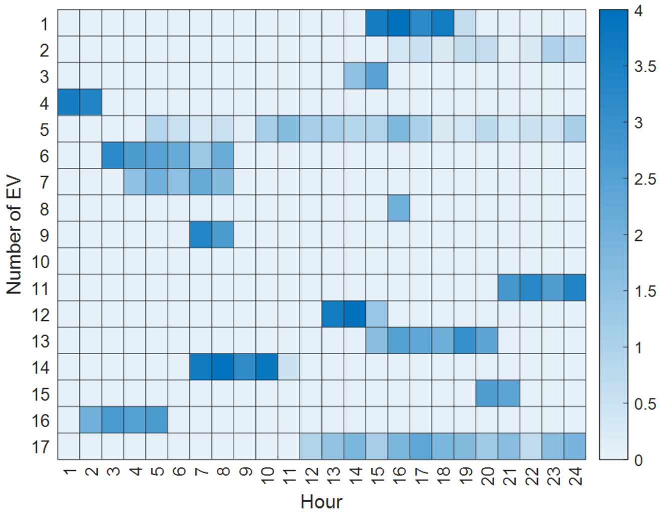

Figure 6. Optimal charging strategy of EV number 35 to 51.

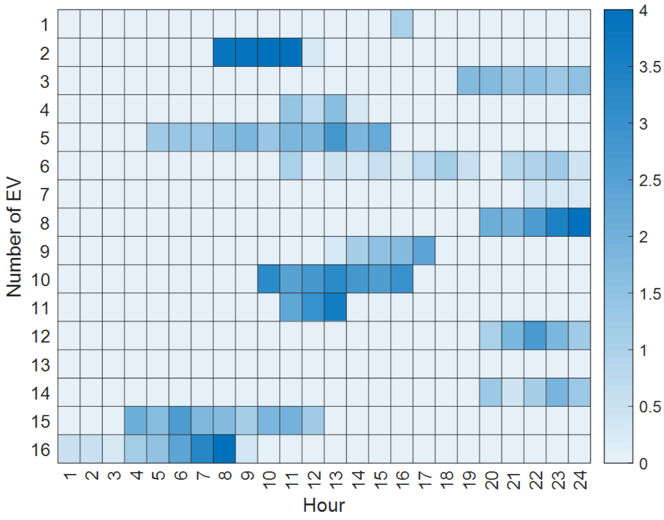

Figure 7. Optimal charging strategy of EV number 52 to 76.

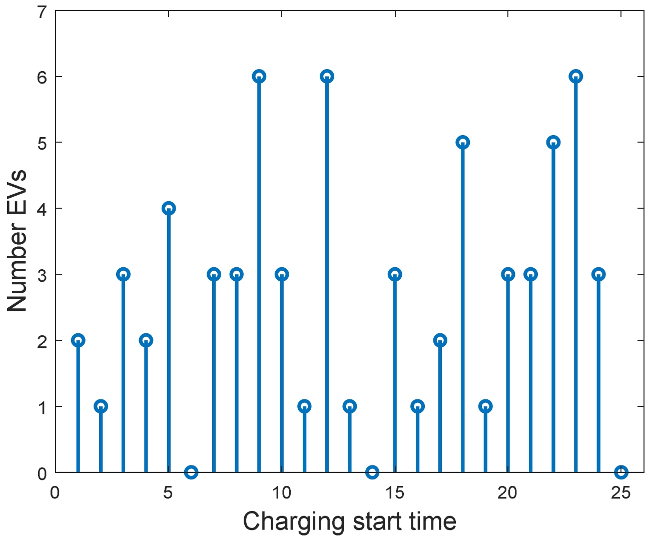

Figure 8. Number of EVs vs. charging start time for optimal results.

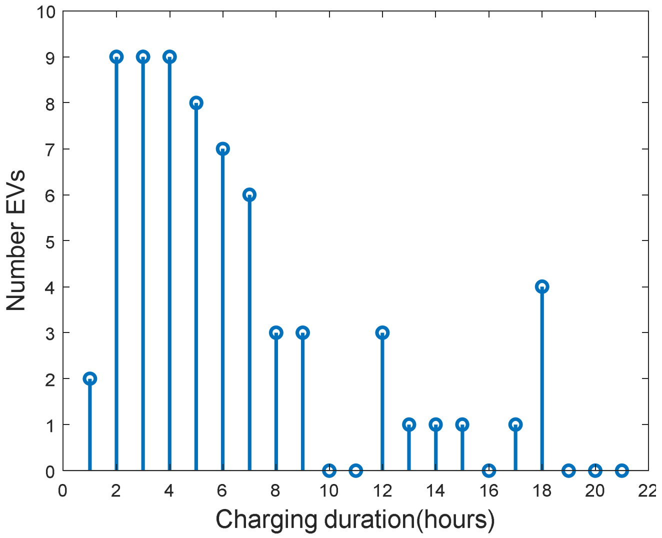

Figure 9. Number of EVs vs. charging durations for optimal results.

TABEL I: PHASES OF NETWORK AND THEIR TOTAL ENERGY DEMAND

	Number of EVs	Total battery Capacity (kWh)	Total initial state-of-charge (kWh)	Total energy demand (kWh)
Phase a	19	380	139	241
Phase b	18	360	146	234
Phase c	30	600	236	344
Total	67	1340	521	819

It is worthwhile to say that the proposed optimal algorithm faces the constraints' dissatisfaction like smart algorithms: – while a constraint, or more is not satisfied, a great penalty will be adding to the objective function which makes the result an unacceptable one, therefore, the algorithm will not follow the result in the next iteration.

VI. CONCLUSIONS

The upcoming integration of a large number of EVs into distribution networks causes significant challenges for operators. The strategy presented in this paper reassures the operators that distribution networks can be operated considering a high penetration of EVs. The optimal application of EVs is considered in condition that the risk of voltage violation, or network overloading, is alleviated. The proposed strategy assumed the condition of near to real operation by testing the presented methodology in an unbalanced three phase load flow analysis. The results have proven that minimizing the total cost of EVs is feasible while network constraints are met. The start time of charging is mainly occurring in off-peak periods, so it helps to smooth the load curve and decrease the expenditures. Meanwhile, the charging duration is between 2 hours and 5 hours. It should be mentioned that the average charging duration is about 5.34 hours. Also, the optimal results are obtained in iteration 10 with less than 1 minute, which decreases the cost. Operating in the allowable range of voltage can be considered as the benefit for operators, while minimizing the total cost encourages the customers to use EVs. As a result, the proposed method considers the benefits for both network operators and EVs' owners.

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